

Survival before annihilation in Ψ' decays

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Abstract

We extend the simple scenario for Ψ' decays suggested a few years ago. The $c\bar{c}$ pair in the Ψ' does not annihilate directly into three gluons but rather survives before annihilating. An interesting prediction is that a large fraction of all Ψ' decays could originate from the $\Psi' \rightarrow \eta_c(3\pi)$ channel which we urge experimentalists to identify. Our model solves the problem of the apparent hadronic excess in Ψ' decays as well as the $\rho\pi$ puzzle since, in our view, the two-body decays of the Ψ' are naturally of electromagnetic origin. Further tests of this picture are proposed, e.g. $J/\Psi \rightarrow b_1\eta$.

1. Introduction

The wealth of recent data from BES and CLEO has led to a welcome revival of interest in charmonium physics. The data now provide an ideal testing ground for theoretical expectations on the decay mechanisms at work in the $c\bar{c}$ system.

The conventional picture of a strong three-gluon annihilation of the Ψ' runs into more and more difficulties. The so-called $\rho\pi$ puzzle and hadronic excess in Ψ' decays pose indeed challenging problems [1].

A few years ago, two of us [2] proposed a simple scheme for the decays of the J/Ψ and the Ψ' . In particular, it was suggested that the Ψ' does not significantly annihilate into three gluons. In this note, we update and sharpen the arguments which led to this somewhat unconventional point of view. In our scenario, all non-electromagnetic hadronic decays of the Ψ' have a simple and general explanation : survival amplitudes. By this, we mean transition amplitudes from Ψ' to lower-lying states which still contain a $c\bar{c}$ pair. One original point of this note is the proposal that the exclusive channel $\Psi' \rightarrow \eta_c + (3\pi)$ could account for a significant fraction (possibly more than 1%!) of all Ψ' decays. We do urge our experimental colleagues to actively search for this forgotten decay mode.

In Section 2 we briefly review and motivate our point of view on $c\bar{c}$ annihilation into gluons. For the Ψ' , *survival precedes annihilation*! More precisely, the $c\bar{c}$ pair survives by spitting out two or three non-perturbative (i.e. with energy much less than 1 GeV) gluons and the lower lying pair then annihilates into three or two perturbative (i.e. with energy $\gtrsim 1$ GeV) gluons, depending on the quantum numbers. These 2+3 or 3+2 annihilation scenarii get rid of the so-called hadronic excess problem in Ψ' decays. Many experimental tests of these ideas are possible.

To lowest order, survival amplitudes are not expected to hadronize in two-body channels. It follows that these decays of the Ψ' should result from a direct electromagnetic annihilation of the $c\bar{c}$ pair. Tests and predictions of this assertion will be discussed in Section 3. In particular, as already emphasized in our earlier paper, the $\rho\pi$ puzzle is then simply solved.

To conclude this note we comment very briefly on some other issues in charmonium physics.

2. Strong $c\bar{c}$ annihilation

It is well known that in the J/Ψ (1^{--}) decays the $c\bar{c}$ pair mainly annihilates into three perturbative gluons ($3g$) or into a photon. The least massive channel into which the $3g$ can materialize is $\rho\pi$ which is indeed the strongest observed hadronic two-body decay [3] of the J/Ψ . However, there is also a significant $c\bar{c}$ survival amplitude namely $J/\Psi \rightarrow \eta_c\gamma$.

Despite the cost of emitting a photon, this decay has the same branching ratio as the $\rho\pi$ channel.

For the Ψ' (1^{--}), the survival radiative decays $\Psi' \rightarrow \gamma + \chi_c$ or η_c ($0^{++}, 1^{++}, 2^{++}$ or 0^{-+}) are quite important. Similarly, the dominant strong decay channels have the structure

$$\Psi' \rightarrow (2NPg) + (3g). \quad (1)$$

The physical picture is as simple as can be : the excited $c\bar{c}$ pair in the Ψ' does not annihilate directly but rather in a two-step process. By spitting out two non-perturbative gluons ($2NPg$), it first survives in a lower $c\bar{c}$ configuration (1^{--} or 1^{+-}) which then eventually annihilates into $3g$. The decays

$$\Psi' \rightarrow (2\pi)J/\Psi \quad (2a)$$

$$\Psi' \rightarrow \eta J/\Psi \quad (2b)$$

clearly follow the pattern of Eq. (1). Particularly important from our point of view is the recently observed [4] survival decay

$$\Psi' \rightarrow \pi^0 h_c. \quad (3)$$

It is also of the type Eq. (1) where the ($2NPg$), the η_0 in this case, mixes with the π^0 . The observed rate implies that the effective $\Psi' h_c \eta_0$ coupling is of the same order as the coupling $\Psi' J/\Psi \eta_0$. At present [3], the survival radiative decays together with the three on-shell channels (Eqs. (2) and (3)) account for more than 80% of all Ψ' decays.

The success of the Gell-Mann, Sharp, Wagner off-shell model [5] for the decay $\omega \rightarrow 3\pi$, namely $\omega \rightarrow \pi + \text{“}\rho\text{”}$, has led us [2] to suggest that decay modes, still of the type Eq. (1),

$$\Psi' \rightarrow 2\pi(0^{++}) + \text{“}h_c\text{”}(1^{+-}) \quad (4a)$$

$$\Psi' \rightarrow \eta(0^{-+}) + \text{“}h_c\text{”}(1^{+-}) \quad (4b)$$

might also be the source of sizeable light hadron decay modes of the Ψ' . The observed [3] and large 5π hadronic decay of the Ψ' could already correspond to the pattern of Eq. (4a) where the “ h_c ” is only slightly off-shell. It would be nice if, for this decay, experimentalists could identify a two-pion invariant mass with the quantum numbers 0^{++} .

There is of course another possibility for a two-step decay pattern

$$\Psi' \rightarrow (3NPg) + (2g) \quad (5)$$

where the lower $c\bar{c}$ configuration (0^{-+} or 0^{++}) annihilates into $2g$. The only on-shell channel for this type of decays is

$$\Psi' \rightarrow (3\pi)\eta_c \quad (6a)$$

to which one may again add the least off-shell amplitude

$$\Psi' \rightarrow 3\pi(1^{--}) + \text{“}\chi_{c0}\text{”}(0^{++}). \quad (6b)$$

Eq. (6a) is an original ingredient of this note. It is a genuine survival amplitude corresponding to the process where the $c\bar{c}$ pair in the Ψ' falls to a lower configuration (η_c) by radiating three non-perturbative gluons which hadronize in 3π . It could easily correspond to 1% or more of all Ψ' decays. An effective calculation (i.e. at the hadronic level) of this decay amplitude requires some guesswork about couplings which leaves room for considerable uncertainty. Details of these calculations will be presented elsewhere. It is however quite interesting to point out that the dominant [3] hadronic decay mode $\Psi' \rightarrow 7\pi$ naturally follows from Eq. (6a). We beg experimentalists to search for a η_c peak in this multi-pion final state.

In summary, Eqs. (1) and (5) are our explanation of the so-called hadronic excess in Ψ' decays. If true, there appears to be no need whatsoever for an important contribution of direct Ψ' annihilation into three gluons. Furthermore, the substitution of one photon for one gluon in Eqs. (1) and (5) allows

$$\Psi' \rightarrow (2NPg) + 2g + \gamma. \quad (7)$$

This 2+2+1 pattern corresponds to on-shell radiative decays such as

$$\Psi' \rightarrow (\pi^+\pi^-)\eta_c\gamma \quad (8a)$$

$$\Psi' \rightarrow \eta\eta_c\gamma \quad (8b)$$

which could be larger than the observed $\Psi' \rightarrow \eta_c\gamma$ mode.

3. Electromagnetic $c\bar{c}$ annihilation

Whether the Ψ' decays following the 2+3 (Eq. (1)) or 3+2 (Eq. (5)) pattern, it seems intuitively difficult to end up with a light hadronic two-body channel. This brings us to the suggestion that these channels are of electromagnetic origin, namely they follow from the direct hadronization of a virtual photon. If such is the case, the $e^+e^- \rightarrow \gamma^* \rightarrow$ hadrons continuum [6] should be consistently subtracted for *all* two-body branching ratios.

In the $SU(3)$ limit for hadrons, a well-known consequence of photon hadronization is that the ratio of branching ratios into neutral and charged strange states is expected to be 4 (for d -coupling). The recent data on $\Psi' \rightarrow K^*\bar{K}$ agree very well with this expectation. Moreover, a striking difference between J/Ψ and Ψ' decay modes is observed [7] in the 3π channel. For the J/Ψ , the $\rho(770)$ almost saturates the two-pion invariant mass, while for the Ψ' it is the $\rho(2150)$ which seems to dominate. Such a strong suppression of the low-lying vector state contributions is not surprising in a high-energy electromagnetic process. These observations considerably strengthen the argument that $\Psi' \rightarrow VP$ is dominantly an electromagnetic process : the so-called $\rho\pi$ puzzle is solved.

Physically, the $1^{+-}0^{-+}$ channel $b_1\pi$ is even more interesting. For the moment [3], it is the largest light hadronic two-body decay of the Ψ' but still of the same order as $\Psi' \rightarrow 2(\pi^+\pi^-)$ which is obviously of electromagnetic nature. If the $b_1\pi$ channel comes from the hadronization of a photon, then both $\Psi' \rightarrow b_1(1235)\eta$ and $\Psi' \rightarrow h_1(1170)\pi^0$ should have branching ratios of the order of 10^{-3} . These processes are certainly welcome to saturate the theoretically well-known $\Psi' \rightarrow \gamma^* \rightarrow \text{light hadrons}$ branching ratio ($\sim 1.6\%$). Moreover, they lead to the surprising prediction that

$$\text{Br}(J/\Psi \rightarrow h_1\pi^0) \approx \text{Br}(J/\Psi \rightarrow b_1\eta) \approx 1\% \quad (9)$$

which are of the same order as the measured $J/\Psi \rightarrow \rho\pi$ branching ratio.

4. Comments and conclusion

The main point of this note has been to reemphasize that there is no experimental necessity for a direct strong annihilation of the Ψ' into $3g$. Why is this annihilation process suppressed? We can only repeat the argument given earlier [2] : the putative (or theoretical) $c\bar{c}$ states ($n^{2S+1}L_J$) are one thing, the physical states are quite another! With strong annihilation of the 1^{--} ground state and its first “radial excitation”, mixing is expected. The QCD dynamics may be such that the physical states, presumably mixtures of the putative ones, are so built up that one of them strongly annihilates into three perturbative gluons while the other does not. Mixing of the 1^3S_1 and 2^3S_1 states via three perturbative gluons has little effect on the charmonium mass spectrum, but may be crucial for the decay pattern. If this explanation is correct, one may wonder about the decay patterns of the 0^{-+} states below the open charm threshold. For the η'_c , we do expect survival to be significantly more important than a direct two-gluon annihilation.

Another comment concerns the 12% rule : we do not see any reason for this rule to be valid. Contrary to the electromagnetic annihilation of the $c\bar{c}$ into a photon which is a pointlike process, neither the J/Ψ annihilation into $3g$ nor the $2+3$ or $3+2$ patterns for the Ψ' are of the same nature except, possibly, in the $m_c \rightarrow \infty$ limit, but then sizeable corrections are to be expected.

To conclude let us repeat that the main points of this short note have been :

1. to revive and make more precise a very simple picture of *all* strong and radiative decay modes of the Ψ' ;

2. to infer that two-body decays of Ψ' into light hadrons are of electromagnetic origin.

These simultaneously solve the so-called hadronic excess and $\rho\pi$ puzzle, respectively. Elegant as this may seem, experimental confirmation is still required. The explicit identification of the decays $\Psi' \rightarrow \eta_c(3\pi), \eta_c(2\pi)\gamma$ and a measurement of the branching ratios for $J/\Psi \rightarrow h_1\pi^0, b_1\eta$ would be important steps in this direction.

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